PLANT SPECIES-AREA RELATIONSHIPS IN TEN NORTH CENTRAL TEXAS PROTECTED NATURAL AREAS

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ABSTRACT

The study of species-area relationships in protected natural areas (PNAs) is an effective tool for designing nature reserves and managing biological diversity. Ten North Central Texas PNAs were studied to understand how plant species richness is related to PNA size. The species-area model was applied to total plant species, native plant species, selected native speciose plant families and invasive plant species. Results indicate that area is a significant predictor of species richness ($r^2 = \geqslant 0.60$) for both total species and native species in North Central Texas PNAs. Habitat diversity as measured by topographic relief and topographic abruptness is also shown to be a significant predictor of plant species richness in North Central Texas PNAs. Introduced species richness could not be predicted from area alone but was explained by perimeter and perimeter/area ratio and one proxy measure of habitat diversity. The estimates of z values range from 0.15 to 0.30, while c ranges from 0.60 to 1.42 for species-area relationships, both of which fall within the range of values estimated by previous research. Such estimates allowed us to evaluate effective management schemes for North Central Texas PNAs plant diversity. The results of this research permit us to examine the invasion of exotic flora in Texas PNAs and to predict how such invasions will reduce native species richness if conservation management practices are not implemented.

RESUMEN

El estudio de las relaciones entre el área y el número de especies en áreas naturales protegidas es una herramienta efectiva para el diseño de reservas y el manejo de la diversidad biológica. Diez áreas naturales protegidas del norte del estado de Tejas fueron estudiadas para entender como la riqueza de especies vegetales está relacionada con el tamaño del área. El modelo especies-área fue aplicado al número total de especies vegetales, las especies nativas, ciertas familias de plantas con muchas especies, y especies exóticas invasoras. Los resultados indican que el área es un predictor significativo de la riqueza de especies ($r^2 \geq 0.60$) para el número total de especies y el número de especies nativas dentro de estas áreas naturales protegidas. La diversidad del hábitat que se midió por medio del total de relieve topográfico y lo accidentado de la topografía también es un predictor significativo de la riqueza vegetal en estas áreas. El número de especies exóticas no se pudo predecir por el área únicamente, sino que se pudo por medio del perímetro del área y la proporción perímetro por área, y uno de los dos estimadores topográficos de diversidad de hábitat. Las estimaciones del valor de z del modelo de MacArthur y Wilson son de 0.15 a 0.30, mientras que la *c* varía desde 0.60 a 1.42 para las relaciones de especies-área. Tales estimaciones nos permiten evaluar los esquemas de manejo de la diversidad vegetal de las áreas naturales protegidas del norte de Texas. Los resultados de esta investigación nos permiten examinar las razones por las cuales las especies exóticas invasoras han colonizado las áreas naturales protegidas y predecir como tales invasiones reducirán la riqueza de especies nativas si no se implementan pautas de manejo para su conservación.

INTRODUCTION

The conservation of biodiversity is a priority issue for ecologists and conservationists worldwide (Myers & Knoll 2001; Novacek & Cleland 2001). As a result, protected natural areas (PNAs) have been created in order to protect, manage and monitor native and endemic biota from habitat destruction and the invasion of introduced and transient species. Such invasions have lead conservationists and ecologists to engage in management programs to preserve natural habitats and prevent extinction. The theory of island biogeography (MacArthur & Wilson 1967) has been used on many occasions in order to measure species richness as well as recommending practices for ecological restoration (Hanski and Matts 1997; He and Legendre 1996; Lawrey 1991; Lomolino et al. 1989). Here we contribute to the existing body of island biogeographic research by examining the floristic richness of ten protected natural areas in North Central Texas.

Island biogeography attempts to document the equilibrium existing between colonization and extinction rates of species on islands. The well-established theory developed by MacArthur and Wilson (1967) uses this equilibrium theory as a focal point for understanding biotic richness on islands and protected areas surrounded by urban, agricultural and forestry developments. This equilibrium is based upon empirical evidence that demonstrates a positive correlation between island size and species richness (Meffe et al. 1997:132). Island biogeography theory explains island biological richness based on the degree of isolation usually measured as the distance from the nearest source habitat. Other factors that influence species richness on islands include colonization rates based upon distance from a source habitat and species turnover based on habitat availability.

Variation in species richness is due in part to the rate at which species can successfully colonize PNAs. Colonization rates can differ and usually depend on the vagility of species able to occupy an area and the distance between island and source habitat. Short-lived species usually colonize areas that have been cleared or severely disturbed. Many PNAs experience high colonization rates because they are adjacent to disturbed source habitats. Colonists of protected areas are commonly exotic species that are managed or introduced into adjacent areas subject to forest exploitation or agriculture (Alverson et al. 1994:83).

Species turnover refers to the balance of immigration and extinction of species continuously enlarged by the arrival of new species from mainland sources and their continuous reduction by extinction through competition for space (Brown & Lomolino 1989). In PNAs and on islands close to continental source habitats, species turnover is greater due to higher colonization rates. Oceanic islands that are the same size but more isolated support lower species richness because of lower species turnover due to lower colonization rates.

The use of island biogeography in PNAs has been a subject of considerable interest for several reasons. The first is that many protected natural areas are effectively islands of a natural habitat in a sea of human dominated ecosystems. Increasingly, PNAs are located in areas where transient species have easy access for invasion. Secondly, these islands of natural habitat usually represent small isolated areas that vary in shape and size which are important criteria particularly relevant for designing and establishing reserves. Finally, the less isolated or the closer an island is to a mainland or source habitat, the more species that island is destined to harbor. Natural dispersal explains the diverse biota of oceanic islands while anthropogenic encouraged dispersal explains the significant encroachment on protected areas by invasive species leading to the loss of native species and the increasing numbers of naturalized exotic species in such areas. Island biogeography has also been used to determine the minimum effective size required for reserves, to characterize community structure, to manage species richness, to measure the effect of disturbance on communities, to estimate extinction rates and for defining conservation biology.

MacArthur and Wilson's (1967:16) initial formulation of the theory of island biogeography ($S=cA^z$, where S = species number, A= area and c and z are constants) indicated that the value of z usually lies between 0.2 and 0.35. Since then, studies have shown that areas located on continents or large islands have z values that range from 0.17 to 0.57. Studies done by Chown et al. (1998:564) empirically derived z values can range from 0.1 to 0.45 for species on oceanic islands. Crawley and Harral (2001) derived z values ranging from 0.18 and 0.57 for spatial scales ranging from 0.01 m^2 to 110 ha for species in southern England. We add empirical support of estimates of z that are in line with those obtained from other continental areas.

Simberloff (1988) and others have argued that area is an effective predictor of species' richness because it is a proxy for habitat diversity. As area increases, so too does habitat diversity. Likewise, other researchers have demonstrated that island elevation and island complexity are significant predictors of species' richness in addition to area . Habitats are an important component of protected areas because they represent the diverse combinations of resources and environmental conditions that plant species can inhabit. The number of differing habitats in a park or reserve can vary tremendously and can result in greater species' number per area. Examples of this have been studied by Williams (1943) who showed that as area increases, so does the diversity of physical habitats. Simberloff (1988) also pointed out that the majority of the species-area relationships documented are in fact accounted for by the fact that larger sites have more species not only because the area is greater but because larger sites have more habitats than smaller sites and that habitat diversity by itself can explain species richness better than area alone. The results of these studies show that habitat diversity is an important component of area that determines species richness so we have made the effort to estimate habitat diversity in North Central Texas protected areas as well.

Many PNAs have lost habitat diversity due to fragmentation and homogenization. Fragmentation is generally accounted for by human activities that disturb or modify natural habitats resulting in the loss of native biota. Invasion of exotic species through habitat disturbance or modification tends to exacerbate the effects on native biota causing further loss of native species. This encroachment on natural landscapes is promoted by agricultural and forestry practices as well as urbanism. The result of such invasions leave PNAs progressively more disturbed as exotic species become more numerous and abundant and losses of native biota increase (Mooney & Cleland 2001).

Edge effects are particularly important in the loss of native species in PNAs. The outer boundary of any habitat island is subject to external factors that modify natural conditions to create novel habitats that can be invaded by species with general habitat requirements (Meffe et al. 1997:294). Edge effects can be especially detrimental because these effects cause PNAs below a certain size or with a significant edge to area relation to lack sufficient natural habitat core area that many native species might need in order to survive. As the natural core area decreases in size, native species are lost and replaced by invasive species that dominate the edges and colonize the core. Invasive species' habitat requirements are often more generalized which allow them to readily invade the protected area's edge. A preponderance of evidence suggests that edge effects play a critical role in PNA management. We examine edge effects by examining PNA perimeter as a predictor of PNA floristic composition.

METHODS

The ten protected natural areas studied are located within the Cross Timbers and Prairies and Blackland Prairies regions in north Central Texas (Fig. 1). The Blackland Prairies consist of about 11,500,000 acres with dark-colored calcareous clays interspersed with gray acid sandy loams (Correll & Johnston 1970; Diggs et al. 1999). The flora typically consists of *Bouteloua curtipendula*, *Bouteloua hirsuta*, *Sporobolus asper*, *Buchloe dactyloides*, *Bouteloua rigidiseta*, *Ulmus crassifolia*, and *Maclura pomifera* and is considered to be true prairie. According to Diggs et al. (1999) the Cross Timbers and Prairies vegetation types encompass roughly 6,879,662 hectares (17,000,000 acres), with 404,686 of those hectares (1,000,000 acres) designated as the East Cross Timbers, 1,214,058 hectares (3,000,000 acres) designated as the West Cross Timbers and 2,630,459 hect-

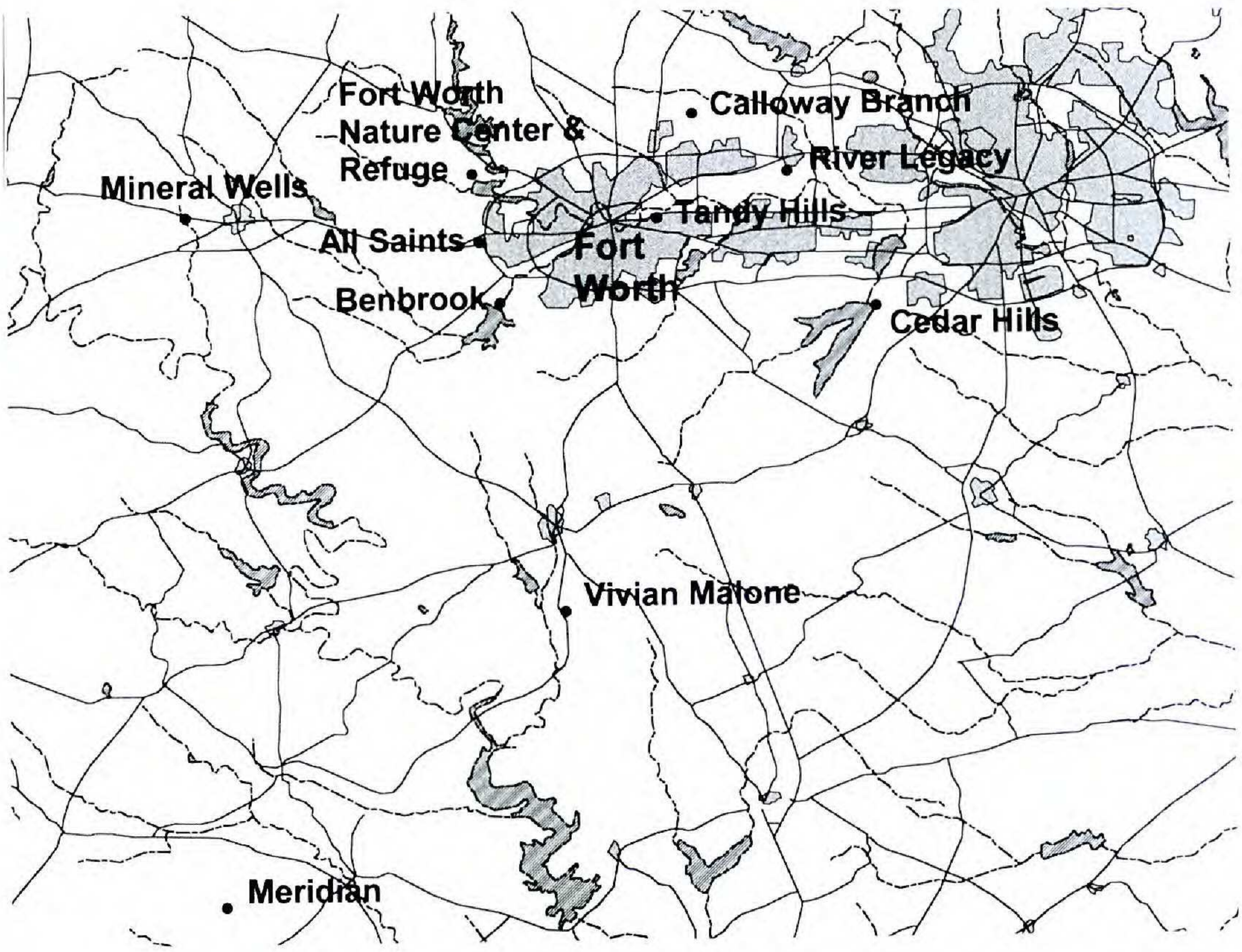

Fig. 1. Location of 10 protected natural areas in north central Texas that are the subject of the present study. Scale is approximately 1:400,000; north is toward the top of the page; gray areas are urban development, shaded areas a reservoirs, gray lines are highways, dash-dotted lines are streams.

ares (6,500,000 acres) as Grand Prairie. These areas range from savanna to dense brush and which consist of Oaks and other woodland vegetation with neutral to slightly acidic clay soils over limestone. The flora consists of *Elymus canadensis*, *Erioneuron pilosum*, and other plants found in the Poaceae family (see Diggs et al. 1999).

Existing plant lists from each of ten PNAs in North Central Texas were analyzed. Six variables were tabulated from each list: total species number, native species number and introduced species number, as well as the number of native legumes, composites and grasses. The number of species in each of these three families was incorporated in our analysis because they are the most species-rich families of the North Central Texas flora and therefore might be significant predictors of habitat loss (Leach et al. 1991:34). These variables were considered the dependent variables in the regression analyses.

Native plant species are those that have been present in a particular area before Columbus (Diggs et al. 1999:11). All other plants that have arrived since then and which are reproducing freely in nature are considered naturalized and were included in the total species count. Introduced species were defined as any species that is not of North American origin and has been introduced since Columbus (Diggs et al. 1999:12). Introduced species recorded in these PNAs include exotic ornamentals (e.g. *Iris* spp., *Narcissus* spp., *Nandina domestica, Photinia serratifolia, Ligustrum* spp. and *Wisteria* spp.) that have been shown to be invasive and capable of becoming serious pests (Diggs et al. 1999:60). However, horticultural species found around buildings or foundations were not included in the introduced species' counts.

Topographic maps were used to locate and examine habitat diversity in each PNA. The maps used are scale 1:24,000 USGS quads for Euless, Hurst, west Cleburne, Covington, Blum, Meridian, Mineral Wells, Benbrook, Haltom City, Lake Worth, Arlington, Duncanville, Cedar Hill, and Britton, Texas. Habitat diversity was estimated using two proxy measures: overall topographic relief and the maximum topographic abruptness over 0.75 mile transects situated in order to maximize the number of contour intervals encountered. The perimeter of each PNA was measured on the same topographic maps. The size of each PNA was based upon data provided by both private and/or public landowners and land-managers.

The model was estimated using linear regression after log transformation of dependent and independent variables. Statistical analysis was accomplished using SPSS and Sigma Plot.

RESULTS

The PNAs range in area from 20.2 hectares (50 acres) to 1416 hectares (3500 acres). Their perimeters range from 1609 m (< 1 mile) to more than 33,796 m (>21 miles). The number of contour lines intersecting 1207 m (0.75 mile) transects ranged from 1 to 22 for topographic abruptness, and topographic relief ranged from 15.25 to 61 m (50–200 ft) (Table 1).

The Asteraceae, Fabaceae and Poaceae were the most speciose families in all ten PNAs. Total species richness ranged from 160 species to 592. Native species richness ranged from 144 to 517; introduced species richness ranged from 15 to 75. Asteraceae species richness ranged from 31 to 76, Fabaceae ranged fromfour to 46 and Poaceae ranged from 15 to 59 (Table 2, Fig. 2). Total species richness increases with PNA size.

Area is a significant predictor of total species richness in North Central Texas PNAs both for total and native species richness as well as for species number in the Fabaceae, Poaceae and Asteraceae ($r^2 \geq 0.4$) (Table 3). Total species richness could be explained 52 percent of the time by area. The estimate of z for total species was 0.18 and c was estimated as 2.03. Tandy Prairie, Vivian Malone, and the Fort Worth Nature Center have higher than average species richness, while other PNAs such as All Saints and Benbrook exhibit low species richness (Fig. 2).

TABLE 1. Physical and geographic characteristics of ten protected natural areas in north central Texas.

PNA*	Area in hectares (acres) (AREA)	Perimeter in meters (miles) (PERI)	Elevation in m asl (ft asl)	Topographic Relief (REL)	Abruptness (ABR)
All Saints	24.3 (60)	1287 (0.8)	229 (750)	20	1
Benbrook	20.2 (50)	1287 (0.8)	212 (694)	48	2
Calloway Branch	40.5 (100)	3058 (1.9)	189 (620)	40	3
Cedar Hills State Park	739 (1826)	23,818 (14.8)	244 (800)	130	14
FW Nature Center	1416.4 (3500)	34,601 (21.5)	181 (594)	101	10
Lake Mineral Wells	1329 (3283)	18,829 (11.7)	259 (850)	160	12
Meridian	204 (505)	6598 (4.1)	317 (1040)	79	5
River Legacy	393 (972)	11,265 (7.0)	183 (600)	73	8
Tandy Hills	64.7 (160)	5150 (3.2)	177 (580)	77	13
Vivian Malone	58.7 (145)	2253 (1.4)	229 (750)	72	9

* Variable acronyms in parentheses.

Native species number (Table 3) is explained by area 54 percent of the time. The estimate of z based on native plant species richness is 0.17, while c is 1.99. Both Tandy Prairie and Vivian Malone display high species richness in comparison to other areas, while Benbrook and All Saints display low native species richness.

Variation in species' number for grasses was explained by area 62 percent of the time. c is 1.34 and z is 0.14. The relationship between grass species richness and area indicates that Tandy Prairie has one of the highest numbers of grass species, followed by Calloway Branch, Vivian Malone and Meridian. Benbrook, All Saints and River Legacy have relatively few grass species by comparison.

Asteraceae species' richness could be explained by area 50 percent of the time. The estimate of c is 1.30, while z is 0.15. The Asteraceae are most abundant in Tandy, Vivian Malone, the Fort Worth Nature Center and Cedar Hills State Park.

Variation in Fabaceae species' richness was explained by area only 46 percent of the time. The estimate of c is 0.60 and z is 0.30. PNAs such as Tandy Hills, Vivian Malone, Calloway Branch and Benbrook have a greater than an average number of legume species.

Area was not a significant predictor of introduced species' richness ($F = 3.5$, $p < 0.1$, $r^2 = 0.30$) (Table 3); however, the number of introduced species could be predicted from perimeter ($F=6.4$, $p<0.04$, $r^2=0.45$). A perimeter/area ratio variable was also a significant predictor of introduced species richness ($F=8.6$, $p<0.05$, $r^2 = 0.52$). Protected natural areas that have high numbers of introduced species have a large perimeter and a high perimeter/area ratio (Figure 2). This indicates that areas possessing more edge per unit area have greater numbers of introduced

TABLE 2. Floristic characteristics of ten protected natural areas in north central Texas.

PNA*	Total Species (TSP)	Native Species (NS)	Introduced Species (IS)	Number Asteraceae (AS)	Number Fabaceae (FS)	Number Poaceae (PS)
All Saints**	160	144	16	29	4	15
Benbrook	184	169	15	31	15	16
Calloway Branch	260	230	30	42	20	28
Cedar Hills State Park	434	375	59	64	33	44
FW Nature Center	592	517	75	76	46	55
Lake Mineral Wells	392	365	27	61	46	40
Meridian	280	258	22	35	26	44
River Legacy	277	250	27	40	18	26
Tandy Hills	437	380	57	63	35	59
Vivian Malone	382	344	38	54	27	37

* Variable acronyms in parentheses. ** List of plants provided by R. Sanders (BRIT)

species. The z values calculated from perimeter and perimeter/area ratio range from 0.3 to 1.1 respectively. Introduced species richness is greatest in Tandy Prairie, Cedar Hills State Park, Fort Worth Nature Center, and Vivian Malone, while the other areas have a lower than average number of introduced species.

Habitat diversity as estimated by topographic abruptness and total topographic relief was a significant predictor of both total species and native species richness. A topographic profile that included the number of contour lines intersecting 0.75 mile transects explained a significant amount of the variation in total species ($F=37.8$, $p<0.001$, $r^2 = .82$) and native species' richness ($F=40.9$, $p< 0.001$; $r^2=0.84$). Overall topographic relief is also a significant predictor of total species' richness ($F=14.9$, $p<0.005$, $r^2=0.65$) and native species' richness ($F=17.4$, $p<0.003$, $r^2=0.83$). c ranges from 1.14 to 2.2 and z varies from 0.41 to 0.55.

DISCUSSION

The estimates of c and z obtained from the plant species and area of these ten protected natural areas in North Central Texas occur within the range established by previous research. MacArthur and Wilson (1967) suggest that z should vary between 0.2 and 0.35 on isolated islands and from 0.17 to 0.19 in continental areas. Other researchers (Chown et al. 1998) have shown that z ranges from 0.10 to 0.45 for the flora and fauna on oceanic islands. Estimates of z for North Central Texas range from 0.14 to 0.30. Estimates of c for these ten North Central Texas protected areas range from 0.58 to 2.03. MacArthur and Wilson showed that c should vary with the degree of isolation and the taxonomic groupings of organisms studied.

Area predicts native species' richness and total species' richness. Habitat

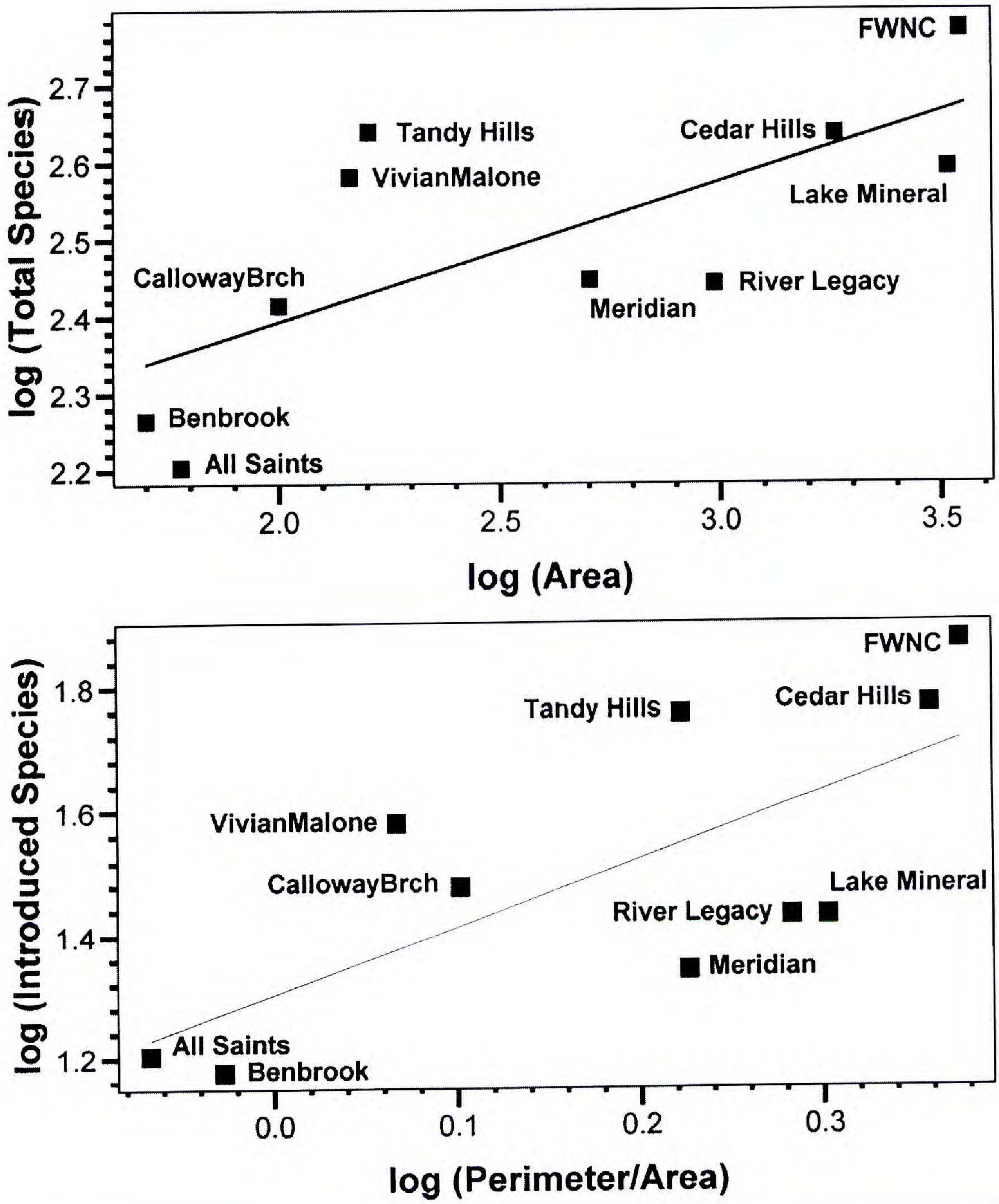

FIG. 2. Above, regression plot of total species and area. Regression parameters are provided in Table 3. Below, regression plot of introduced species and perimeter/area.

diversity as estimated by topographic abruptness and overall topographic relief explain species' richness for both native and total species. Estimates of habitat diversity appear to better explain species richness than area. Our results confirm those of other researchers who show that habitat diversity is generally a better predictor of species richness presumably because greater topographic

TABLE 3. Regression equations and test statistics for floristic richness indicators of ten protected natural areas in north central Texas. Variable acronyms can be found in Tables 1 and 2.

TSP = 2.03 + 0.18 (AREA)	$r^2 = 0.52$	$F = 8.8$	$p < 0.05$
NSP = 1.99 + 0.18 (AREA)	$r^2 = 0.55$	$F = 9.6$	$p < 0.05$
ASP = 1.31 + 0.14 (AREA)	$r^2 = 0.46$	$F = 6.8$	$p < 0.05$
LSP = 0.58 + 0.30 (AREA)	$r^2 = 0.46$	$F = 6.9$	$p < 0.05$
PSP = 1.06 + 0.18 (AREA)	$r^2 = 0.40$	$F = 5.1$	$p < 0.05$
ISP = 1.02 + 0.19 (AREA)	$r^2 = 0.30$	$F = 3.5$	ns
ISP = 1.30 + 0.30 (PER)	$r^2 = 0.45$	$F = 6.4$	$p < 0.05$
ISP = 1.30 + 1.09 (PER/AREA)	$r^2 = 0.52$	$F = 8.6$	$p < 0.05$
TSP = 2.20 + 0.42(ABR)	$r^2 = 0.82$	$F = 37.8$	$p < 0.001$
NSP = 2.14 + 0.41(ABR)	$r^2 = 0.84$	$F = 40.9$	$p < 0.001$
ISP = 1.13 + 0.48 (ABR)	$r^2 = 0.62$	$F = 13.0$	$p < 0.01$
TSP = 1.49 + 0.55(REL)	$r^2 = 0.65$	$F = 14.9$	$p < 0.005$
NSP = 1.40 + 0.55 (REL)	$r^2 = 0.83$	$F = 17.4$	$p < 0.05$
ISP = 0.51 + 0.54 (REL)	$r^2 = 0.35$	$F = 4.2$	ns

relief provides for a greater variety of habitat types offering more opportunities for a greater number of species (Simberloff 1988).

Introduced species' number could not be explained by area. Both perimeter and perimeter/area ratio explain a significant amount of the variation in introduced species across protected areas. The PNAs with a high number of introduced species have a high perimeter/area ratio suggesting some of these protected areas are fragments of natural habitat with permeable edges. High perimeter to area ratios increase PNA's permeability to invasive species. The easy invasion of introduced species, many of which are weedy intruders that are often wind dispersed and/or horticultural exotics that produce an abundance of enticing seasonal fruits that are dispersed by birds and omnivorous mammals are not only invasive but pernicious.

Our analyses demonstrate that management plans are necessary to conserve the native species still existing in the protected natural areas of north central Texas by preventing the invasion of non-native species. It is possible that for every introduced species that is successfully surviving in these PNAs, a native species might be displaced. The ongoing competition between native and introduced species will continue until these areas are managed appropriately or the amount of edge relative to area diminishes. These areas were probably once subject to periodic fires (Leach & Givnish 1991) which allowed the native biota to colonize open areas and survive more abundantly than introduced species in north central Texas. Such periodic fires have worked in the past to create and maintain suitable environment for native species and a detrimental environment for most introduced species. Most of the invasive species that are now successfully colonizing these areas are not only successful, but they are naturalizing relentlessly because periodic fires are no longer allowed.

It has long been argued that the optimal shape for a refuge should be circular and that small linear protected areas have a greater chance of becoming significantly modified by invasive species (Simberloff 1988:479) which change protected natural areas into protected anthropogenic areas. As a result, park or reserve shape, the amount of edge relative to area, and park size continue to be debated because although the model can predict species richness based upon area, it fails to incorporate park shape and edge-area considerations. In this study we have shown that many of the areas have an existing shape and size that grant increased access to invasive plant species.

Appropriate management of these PNAs in North Central Texas should take two courses of action. One focus would be to increase park size, especially for those areas that exhibit high perimeter/area ratio, including Tandy Stratford Prairie, Vivian Malone and the Fort Worth Nature Center. By doing this, edge effects will diminish by increasing the core area where many native and some endemic species still thrive. Adding area to these PNAs could potentially buffer them from edge effects (boundary permeability) and enhance their ability to maintain native species' richness. Adding area is perhaps difficult because of competition from more lucrative land-use options. An alternative to increasing their size might be to impose zoning restrictions in land developments adjacent to these PNAs. Restrictions on planting native species in urban areas found near PNAs could diminish the influx of non-native species that typically invade and colonize such areas (e.g. *Nandina* spp., *Photinia* sp., *Ligustrum* spp). Coupling restrictions on urban plantings and increasing the size of PNAs would insure that native species in PNAs would be protected better than the smaller reserves in the urban landscape because larger, protected sites are more likely to be able to accommodate disturbance than small, unprotected reserves.

In conclusion, the conservation of PNAs is an ongoing process. Disturbance takes place inside and out, succession follows and colonization by both native and introduced species will continue. One of the most critical concerns should be to determine which species will be successful in the long run. Incorporating appropriate conservation management schemes will make it possible to lower extirpation rates and insure the native species' likelihood of survival. Protected natural area size, shape, habitat diversity, edge effects, proximity to disturbed communities, and distance from source habitats all play important roles in maintaining the natural biota in PNAs. We believe that the use of the species-area model will aid in managing and controlling PNAs' species composition and give the public an idea of how invasion of introduced plant species can be harmful to such areas now and in the future.

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